

The Great Proton Search Continues

Kenneth A. LaBel

ken.label@nasa.gov

**Co-Manager, NASA/OSMA, NASA Electronic Parts and
Packaging (NEPP) Program**

**Ad hoc proton “team” formed by NASA OSMA/NEPP along with Air Force Space
and Missiles Center (AFSMC), NRO, and Department of Energy (DOE) with
support from industry and university partners**



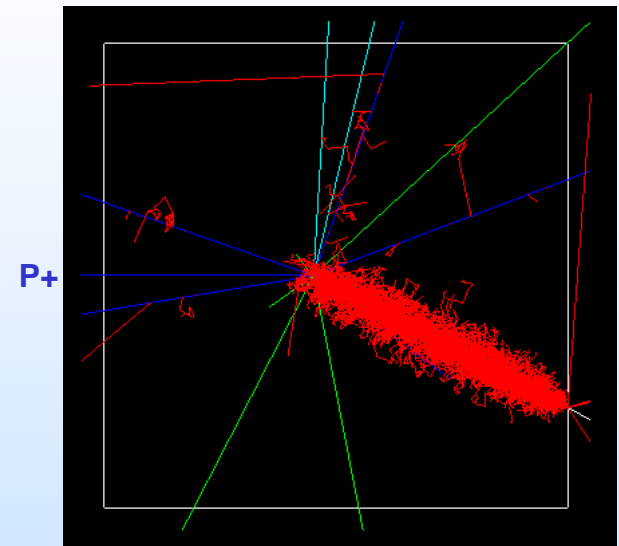
Acronyms

- Three Dimensional (3D)
- Air Force Space and Missiles Center (AFSMC)
- also know as (AkA)
- Automated Test Equipment (ATE)
- Californium (Cf)
- Crocker Nuclear Laboratory (CNL)
- Crocker Nuclear Lab (CNL)
- TBD - current year 2017 ??? (CY17)
- Displacement damage dose (DDD)
- Department of Energy (DOE)
- Device Under Test (DUT)
- Galactic Cosmic Rays (GCRs)
- Glenn Research Center (GRC)
- Hampton University Proton Therapy Institute (HUPTI)
- International Business Machines Corporation (IBM)
- Integrated Circuits (ICs)
- Indiana University Cyclotron Facility (IUCF)
- Johnson Space Center (JSC)
- Los Alamos Neutron Science Center (LANSCE)
- Lawrence Berkeley National Laboratories (LBL)
- linear energy transfer (LET)
- Cyclotron, linear accelerator (LINAC)
- Loma Linda University Medical Center (LLUMC)
- Massachusetts General Hospital (MGH) Francis H. Burr Proton Therapy Center
- Military Standard (MIL-STD)
- Math and Physics Sciences (MPS)
- n-type charge coupled device (n-CCD)
- NASA Electronic Parts and Packaging (NEPP) Program
- National Reconnaissance Office (NRO)
- Office of Safety and Mission Assurance (OSMA)
- research and development (R&D)
- South Atlantic Anomaly (SAA)
- SCRIPPS Proton Therapy Center (SCRIPPS)
- second (sec)
- Single Event Effects (SEE)
- Soft Error Rate (SER)
- size, weight, and power (SWaP)
- Texas A&M University (TAMU)
- to be determined (TBD)
- Total ionizing dose (TID)
- Tri-University Meson Facility (TRIUMF)
- University of Maryland Proton Therapy Center, Baltimore (U MD)
- University of California at Davis (UCD)
- University of Florida Proton Health Therapy Institute (UFHPTI)
- Van de Graaff (VDG)
- Van de Graaffs (VdGs)



Outline

- Abstract and Problem Statement
- Proton Effects on Electronics
- Potential Users
- Electronics Testing with Protons
- Domestic Proton SEE Facilities
 - High Energy (>200 MeV)
 - Medium Energy (50-125 MeV)
- Summary/Comments



Sample 100 MeV proton reaction in a 5 um Si block. Reactions have a range of types of secondaries and LETs. Complicating statistics and testing. (after Weller, *Trans. Nucl. Sci.*, 2004)



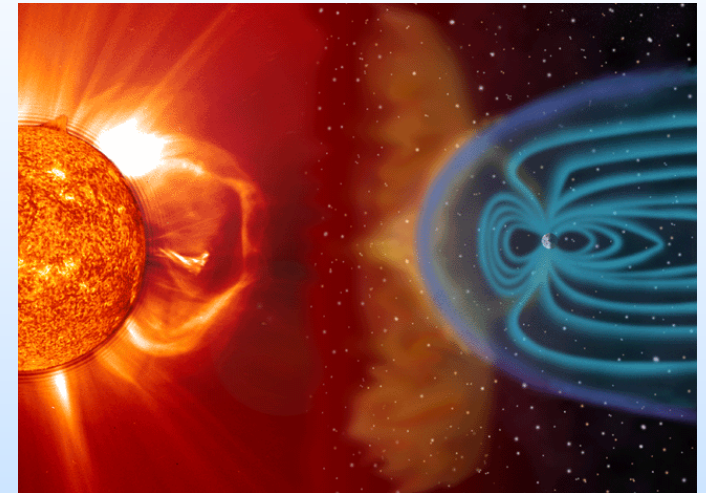
Abstract and Problem Statement

- **Abstract**
 - This presentation is an outbrief of the current team status for access to domestic high (>200 MeV) energy proton facilities. In addition, future considerations will be discussed.
- **Problem Statement (Space Electronics)**
 - Particle accelerators are used to evaluate risk and qualify electronics for usage in the space radiation environment
 - Protons simulate solar events and trapped proton in planetary magnetic fields
 - Domestic sources for these particles are becoming more limited due to facility closures or reduction of accessible hours.
 - Indiana University Cyclotron Facility (IUCF) – CLOSED 2014 - ~2000 hours of space electronic user needs annually
 - SCRIPPS Proton Therapy Center – announces bankruptcy on March 2, 2017



Proton Radiation Effects and the Space Environment

- Three portions of the natural space environment contribute to the radiation hazard
 - **Free-space particles**
 - Galactic Cosmic Rays (GCRs)
 - For earth-orbiting craft, the earth's magnetic field provides some protection for GCR
 - **Solar particles**
 - Protons and heavier ions
 - **Trapped particles (in the belts)**
 - Protons and electrons including the South Atlantic Anomaly (SAA)
- Hazard experience is a function of orbit and timeframe



The sun acts as a modulator and source in the space environment,
after Nikkei Sciences
J. Barth, NSREC Short Course, 1998.

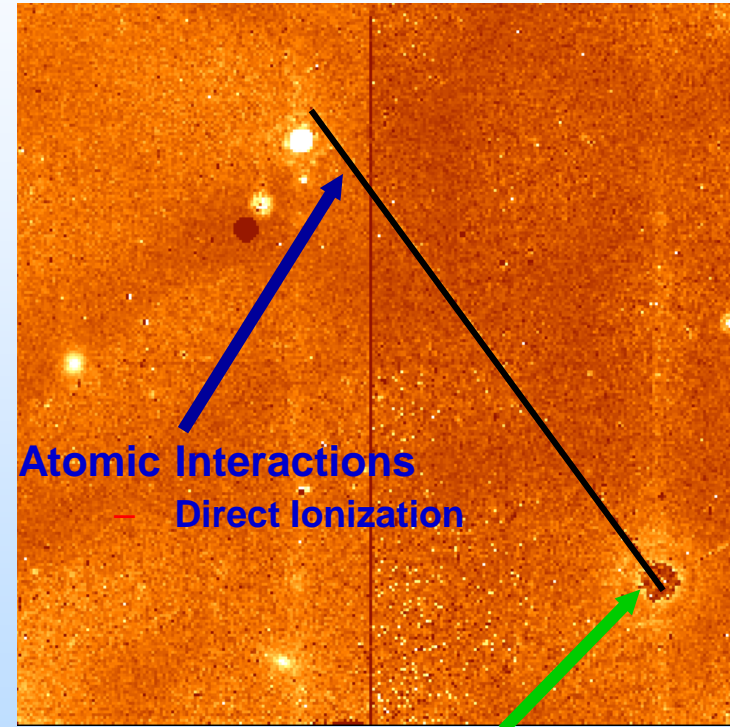


Radiation Effects and Electronics

- Ground testing is performed to qualify electronics for space usage
 - Long-term cumulative degradation causing parametric and/or functional failures
 - Total ionizing dose (TID)
 - Displacement damage dose (DDD)
 - Transient or single particle effects (Single event effects or SEE)
 - Soft or hard errors caused by proton (through nuclear interactions) or heavy ion (direct deposition) passing through the semiconductor material and depositing energy
 - Heavy ion tests on the ground are used to bound risk for space exposure to GCRs and some solar particles
 - Proton tests on the ground aid risk analysis for any orbits exposed to trapped protons (Space Station, for example) or solar protons.
 - Useful for SEE and DDD evaluation

Particle interactions with semiconductors
Image from the Space Telescope Science Institute (STScI), operated for NASA by the Association of Universities for Research in Astronomy

<http://www.stsci.edu/hst/nicmos/performance/anomalies/bigcr.html>



Interaction with Nucleus

- Indirect Ionization
- Nucleus is Displaced
- Secondaries spallated



Typical Ground Sources for Space Radiation Effects Testing

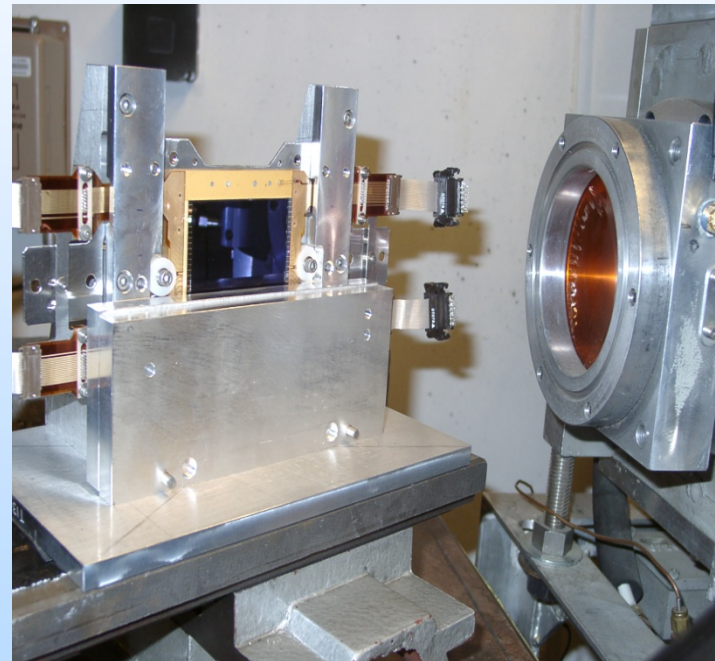
- Issue: TID
 - Co-60 (gamma), X-rays, Proton

- Issue: DDD
 - Proton, neutron, electron (solar cells)
 - Cyclotron, linear accelerator (LINAC), Van de Graaff (VDG) accelerator

- SEE (GCR)
 - Heavy ions
 - Cyclotrons, synchrotrons, VDGs
 - Lesser utility: Cf sources

- SEE (Protons)
 - Protons ($E > 30$ MeV) – primarily nuclear interactions
 - $E > 200$ MeV is “space sweetspot”
 - Protons (~ 1 MeV) – direct ionization effects in very sensitive electronics
 - Cyclotrons, synchrotrons

← *TID is typically performed at a local source with nearby automated test equipment (ATE). All others require travel and shipping with commensurate limitations/costs.*



Hubble Space Telescope Wide Field Camera 3
E2V 2k x 4k n-CCD
in front of Proton Beam at UC Davis
Crocker Nuclear Lab (CNL).
Photo by Paul Marshall, consultant to NASA



Space Electronics Users

NASA, other Government, Industry, University – International base

- **Space Electronic Systems – Projects, Manufacturers**
 - Perform **qualification** tests on integrated circuits (ICs)
 - Perform **system validation/risk** tests on assembled hardware (boards/boxes)
- **Semiconductor Research**
 - Perform exploratory **technology sensitivity** tests on new devices/technology in advance of flight project usage or to **evaluate radiation hardening techniques**
 - Perform testing to **develop and define qualification (test) methods**
- **Semiconductor Industry – Product Development/Validation**
 - Performs tests on their new products for **MIL-STD qualification** as well as **preliminary sensitivity** tests on devices under development
 - Commercial terrestrial products use protons for soft error rate (SER) testing in lieu of neutrons
 - Avionics, automotive, etc... test for safety critical validation



Who Else is Interested in Proton Research Facilities

- **Other Space Users**
 - Human Radiation Protection (biological sciences)
 - Material/shielding Studies (physical sciences)
 - Solar cells (damage studies)
- **Terrestrial Soft Error Rate (SER) Simulation**
 - *Protons may be used as an accelerated test for terrestrial neutron effects*
 - Important for
 - Automotive (Safety Critical Electronics)
 - High Reliability Computing, etc...
 - Medical Electronics
 - Example: Reliability of implantable electronics
- **Atmospheric Neutrons**
 - Aircraft and avionics systems



Space and Other Researchers - Comments

- **When IUCF closed in 2014, ~2000 research hours (mostly used by space electronics and semiconductor manufacturers)**
 - **This need has not diminished, but has INCREASED**
 - **Semiconductor industry – Increased reliability concerns from space to ground**
 - Advanced technologies (ex., <14nm feature size devices)
 - New architectures (3D structures)
 - New materials (roles of secondaries and fission products)
 - Replacement testing for terrestrial neutron effects (can do in hours what may take weeks in a neutron source)
 - **Space Users**
 - Increased use of commercial electronics for higher performing and smaller size, weight, and power (SWaP) systems. Examples:
 - » Advent of CubeSats – interest in risk reduction tests
 - » Commercial Space – companies like SpaceX and OneWeb use protons for electronic assurance
 - **Automotive**
 - Exploding industry for automotive electronics (driver assist, self-driving, etc...) – Safety Critical aspects



Basic Space Electronic Requirements for High Energy Proton Facility

- **Energy range:**
 - 125 MeV to > 200 MeV
- **Proton flux rates:**
 - $1e7$ p/cm²/sec to $1e9$ p/cm²/sec
- **Test fluences:**
 - $1e9$ p/cm² to $1e11$ p/cm²
- **Irradiation area:**
 - Small (single chip ~ 1cm) to board/assembly > 15cm x 15cm
- **Beam uniformity:**
 - >80%
- **Beam structure:**
 - Cyclotron **preferred** (random particle delivery over time)
 - Pulsed beam acceptable for some applications
 - Fixed spot or scatter (random particle delivery over area)
 - Scanning beams MAY be acceptable but need to consider device or system under test operations versus timing of beam spots



Sample Considerations for Electronics Proton Testing at Cyclotrons

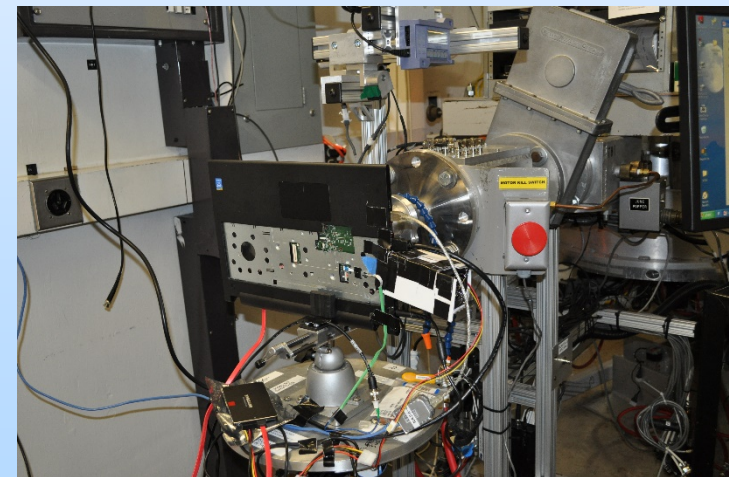
- **Particle**
 - Dosimetry/particle detectors
 - Uniformity
 - Energy mapping to the space environment
 - Particle localization
 - Stray particles (neutrons, for example)
 - Beware of “scatter” design
 - Particle range
 - Flux rates and stability
 - Beam structure
 - Beam spills
- **Practical**
 - Cabling
 - Thermal
 - Speed/performance
 - Test conditions
 - Power
 - Mechanical
 - Staging area
 - Shipping/receiving
 - Activated material storage
 - Operator model (who runs the beam)



Diatribes: Increasingly Complex Electronics

- Two drivers for SEE response during testing:
 - Geometric: number of transistors (ion targets) in DUT
 - Temporal: when the target is hit versus operations in a device
 - Aka, state-space coverage
- Challenge:
 - Beam time optimization versus “risk management”

**Billion transistor device + Billion operating states =
Impossibility of Full Coverage during a Test Campaign
(or in our lifetime!)**



*Testing of Intel Broadwell Processor at TAMU,
Ken LaBel*



Proton Facilities for Electronics Testing – 200 MeV regime

- **Active Proton Research Facilities**

- **Massachusetts General Hospital (MGH) Francis H. Burr Proton Therapy Center**
 - Provides 24 hours for 3 out 4 weekends a month
 - Highly used by industry and all Agencies
 - Overbooked already for CY17!
- **Tri-University Meson Facility (TRIUMF) – Vancouver, CAN**
 - Runs 4 cycles a year with two beam lines (105 and 500 MeV)
 - Very busy with semiconductor and terrestrial electronics
- **Loma Linda University Medical Center (LLUMC)**
 - Weekend usage with some available time beyond current load
 - Have recently installed improvements
- **SCRIPPS Proton Therapy Center**
 - Announced bankruptcy on March 2, 2017 – tbd future
 - Has 4 industry user contracts with limited additional users (i.e., “large” users only – 100 hrs/yr each)



Proton Facilities for Electronics Testing – 200 MeV regime

- **Proton Cancer Therapy Facilities – Nearly Research Ready or Limited Access**
 - **Cincinnati Children's Proton Therapy Center**
 - Nice separate research room with model similar to IU (interleaving weekdays with patients – no weekends)- Same cyclotron as SCRIPPS
 - Expect fall '17 opening for customers; shakeout test planned later in '17
 - **Northwestern Chicago Proton Center (former Cadence)**
 - IBA Cyclotron taking limited customers (NASA only?)
 - **Mayo Clinic**
 - Two proton facilities (Rochester, MN and Phoenix, AZ) – synchrotron, but unique duty cycle
 - Shakeout test in June 2017 in Rochester; expect limited sales later in '17
 - Research room built and have experience with government contracts
 - **Hampton University Proton Therapy Institute (HUPTI)**
 - Planning to open research room later in 2017
 - Weekdays with beam interleaving w patients
 - Still in planning
 - **MD Anderson**
 - NASA/JSC evaluating with The Aerospace Corp
 - **U Penn Roberts Proton Therapy**
 - Research room under commissioning



Proton Facilities for Electronics Testing – 200 MeV regime

- **Proton Cancer Therapy Facilities – Finishing Commissioning**
 - U MD Proton Therapy Center (Baltimore)
 - Planning on taking customers later in '17 w/ NASA shakeout test prior
 - Possible similar operating mode to SCRIPPS (weekends, large users – 200 hrs/yr total)
 - University of Florida Proton Health Therapy Institute (UFHPTI)
 - Completing medical commissioning
 - TBD yearly hours available to community but expect ~200 hours/year
 - Expect shakeout test later in '17
- **Proton Research Facilities – Unknown Status**
 - Case Western University Hospital Seidman Cancer Center
 - NASA GRC working an agreement with expected visit – on hold?
 - Waiting on lawyers
 - Small facility with expected limited hours (but great location for GRC!)
 - ProVision (Knoxville)
 - TBD – 2 rooms opening with TBD excess capacity in TBD timeframe in 2017
 - limited responsiveness
- **Proton Research Facilities – Proposals for Dedicated Research**
 - Los Alamos Neutron Science Center (LANSCE)
 - Has 800 MeV proton source with white paper to modify for SEE test purposes
 - Visited in 1QFY17 – requested support and aid in obtaining funding
 - Question remains on beam structure



Medium Energy Proton Cyclotrons

- **Commonly used medium energy proton facilities (some SEE, some DDD):**
 - University of California at Davis (UCD) Crocker Nuclear Laboratory (CNL) – (63 MeV)*,
 - Lawrence Berkeley National Laboratories (LBNL)* – (55 MeV), and,
 - Texas A&M University (TAMU) – ~50 MeV.
- **LBL's future is uncertain for continued access.**
 - Trade space between government sustaining funds and return on science and aerospace needs. FY18 budget question for Dept of Energy...
- **CNL continues to support electronics test user community**
 - Reorganized under Math and Physics Sciences (MPS) Department
 - Currently have 43 contracts in place with our community
 - Facility has been a staple for testing of optics/sensors/etc...
 - **Comments from CNL (March 2017)**
 - Pursuing a large multi-disciplinary DOE radioisotope development program which will support more lab staff, operations, and R&D.
 - “The additional work will only add stability to the lab for the SEE community.” - Spencer Hartman, Head Space and Radiation Effects Facility & Cyclotron Laboratory, CNL
 - Also adding a neutron spallation beam line
 - A high flux beam line ($1\text{E}15 \text{ p/cm}^2\text{-s}$) for Large Hadron Collider research and development.

** also in use for low energy proton testing*



Summary

- **Volatility is the name of the game for proton research access**
 - The uncertainty of cancer therapy facilities for utilization and business models (insurance, physician acceptance, locality) make assured access questionable.
 - However, near term access appears to be improving... but give it a week and it may change
 - Hope to add several facilities to the “truly available access” list
- **Need is clearly growing and could be marketed more effectively**
 - Participation in electronics radiation effects conferences, for example
- **Unclear if there’s a business case for dedicated research facility unless government subsidized**
 - LANSCE?
 - Purchase of “failed” therapy center?
 - Other?